REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
03/29/2012

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
01/01/06 - 12/31/11

4. TITLE AND SUBTITLE
Modeling the Effects of Internal Waves on Long-Range Propagation

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-06-1-0194

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Frank S. Henyey

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Applied Physics Laboratory
University of Washington
1014 NE 40th Street
Seattle, WA 98105

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Robert H. Headrick, ONR 322
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project aims to understand the fluctuations in low frequency (100 Hz, for example) acoustical propagation in the ocean over long distances (50 km to thousands of km.), as well as other effects of internal waves and other small-scale variability in the speed of sound. The objective is to model results of recent low-frequency, deep-water acoustic-propagation experiments, constraining the model environment from the measurements of those environments. Phenomena such as intensity fluctuations, deep arrivals, and spatial correlations are of more concern than travel time fluctuations, as the physics of travel time fluctuations is much better understood.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Frank S. Henyey
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	6	(206) 543-4856

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Modeling the Effects of Internal Waves on Long-Range Propagation

Frank S. Henyey
Applied Physics Laboratory, University of Washington
email: frank@apl.uw.edu

Award Number: N00014-06-1-0194

This project aims to understand the fluctuations in low frequency (100 Hz, for example) acoustical propagation in the ocean over long distances (50 km to thousands of km.), as well as other effects of internal waves and other small-scale variability in the speed of sound. The objective is to model results of recent low-frequency, deep-water acoustic-propagation experiments, constraining the model environment from the measurements of those environments. Phenomena such as intensity fluctuations, deep arrivals, and spatial correlations are of more concern than travel time fluctuations, as the physics of travel time fluctuations is much better understood. Intensity fluctuations, deep arrivals, and spatial correlations are primarily due to smaller scales in the environment than are travel time fluctuations.

In work done under a previous grant, I showed that the acoustic effects of these smaller scales cannot be properly described by ray tracing. More recently, the deep arrivals observed in LOAPEX, a long-range acoustic propagation experiment in the North Pacific during 2004, were modeled with full-wave methods. Deep arrivals are sound arrivals that extend to depths that would be quiet at their arrival time, but would only occur one to several seconds earlier, if there was no small-scale sound speed variability. The depth extent of these deep arrivals could be successfully modeled with a reasonable model of the sound speed fluctuations, but the depth extent was much to small if ray tracing was used.

Internal waves and spice from CTD profiles

An analysis of environmental data was carried out to separate the physical processes leading to small-scale sound speed fluctuations. Small-scale internal waves and "spice" are the processes of concern. CTD (conductivity, temperature, depth as measured by pressure) profiles are used to extract the small-scale internal waves and "spice".

Small-scale internal waves and spice fluctuations have been extracted from CTD profiles in three experiments, LOAPEX and two Philippine Sea experiments of 2009 and 2010. The vertical wavelength spectra of these results have been evaluated. Acoustic simulations of intensity fluctuations for the 2009 experiment have been done. First results from a coupled mode approach have been obtained.

The CTD profiles show that the internal waves are consistent with a modified Garrett-Munk model. Enough is known about internal waves so that we can have some confidence that such a model is a good description of the internal wave field. The strength of the internal wave field relative to the Garrett-Munk average value varied from 0.5 at LOAPEX to about 1.4 in the Philippine Sea. The spice contribution is large in LOAPEX and in the 2010 Philippine Sea experiment, but is small in the 2009 experiment and in that part of the 2010 experiment located close to the positions of the 2009 CTD profiles.

The vertical spectra of internal wave and spice strains from the two PhilSea experiments are shown in figures 2-4. Although spectra of spice are shown, a spectral model is not an adequate model. The spice fluctuations are highly intermittent, instead of being close to a Gaussian process. Moreover, the horizontal structure of spice and its relationship to the measured vertical structure are unknown. These features are expected to be important to acoustic propagation. A towed CTD chain that was deployed was intended to measure these features, but the data may be inadequate to resolve the strucure of the spice.

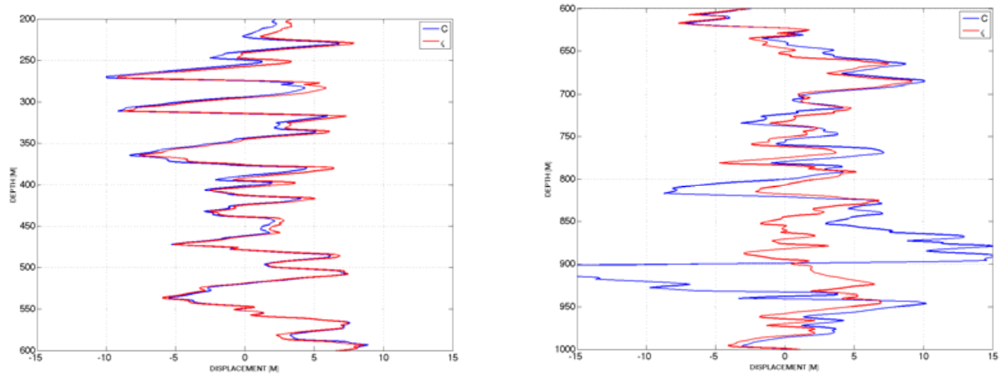

Figure 1: Representative 400 m sections of small-scale density displacement (red curves) and sound speed pseudodisplacement (blue curves). The displacement axes in both panels extend from -15 m to 15 m. The left panel is from the PhilSea 2009 experiment, and the right panel is from LOAPEX. The example on the left has very little difference between the density and sound speed displacement profiles, indicating that only internal waves are present. The profile on the right has significant spice, making the sound speed pseudodisplacement fluctuations larger than the density displacement fluctuations.

West of longitude 127° E, The amount of spice fluctuations is rather small. For acoustic propagation limited to that region (in both 2009 and 2010), an internal wave model of the usual type is reasonably correct. However, east of that longitude in 2010, such a model is not likely to correctly predict the acoustics.

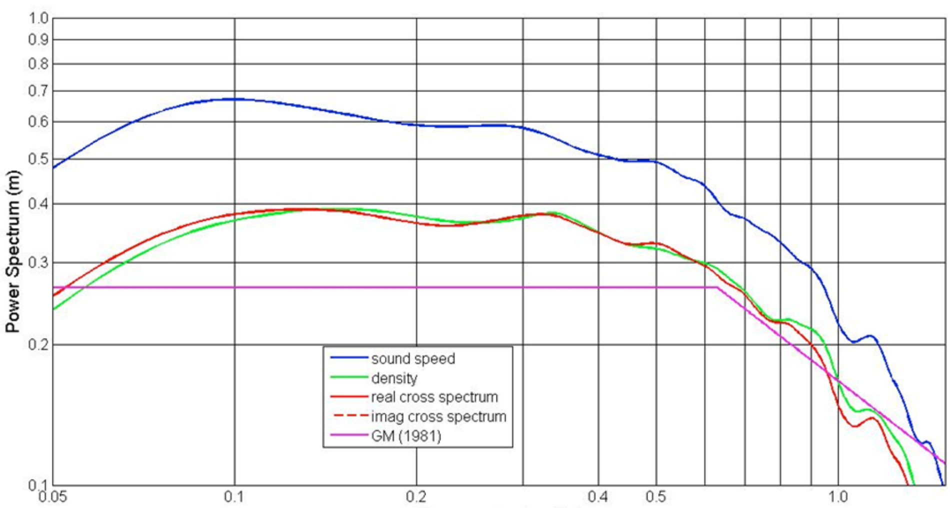

Figure 2 The average strain spectra for the 2010 Philippine Sea experiment. The spectrum defined from density only contains internal waves, it has the same shape as the Garrett-Munk spectrum, and it is smaller than that defined from sound speed, which contains both internal waves and spice. The cross spectrum agrees with the density defined spectrum, validating the method. The imaginary part of the cross spectrum is tiny, and lies below the bottom of the graph. The spice spectrum, which is the difference, is not small compared to the internal wave spectrum.

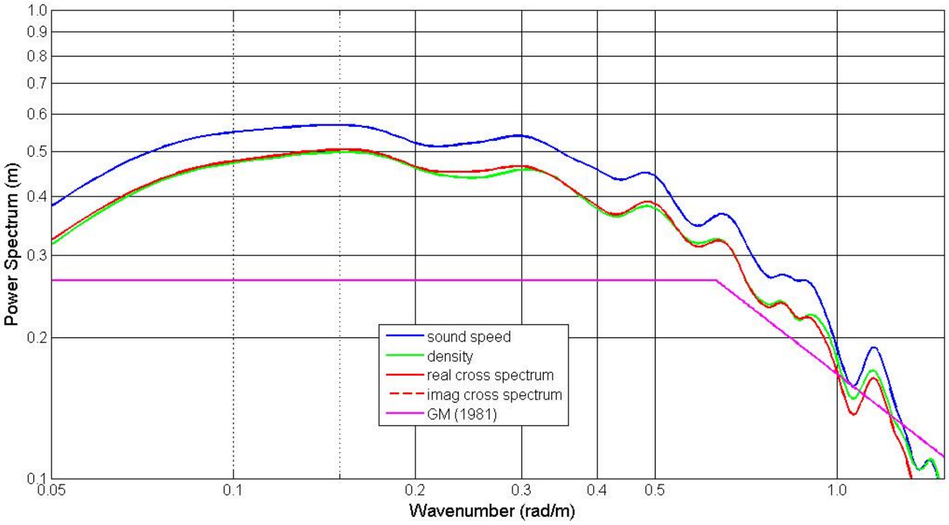

Figure 3 The same as figure 1, but the data are restricted to those taken west of longitude 127° E. For these data, the spice contribution is much less significant than in the totality of the data.

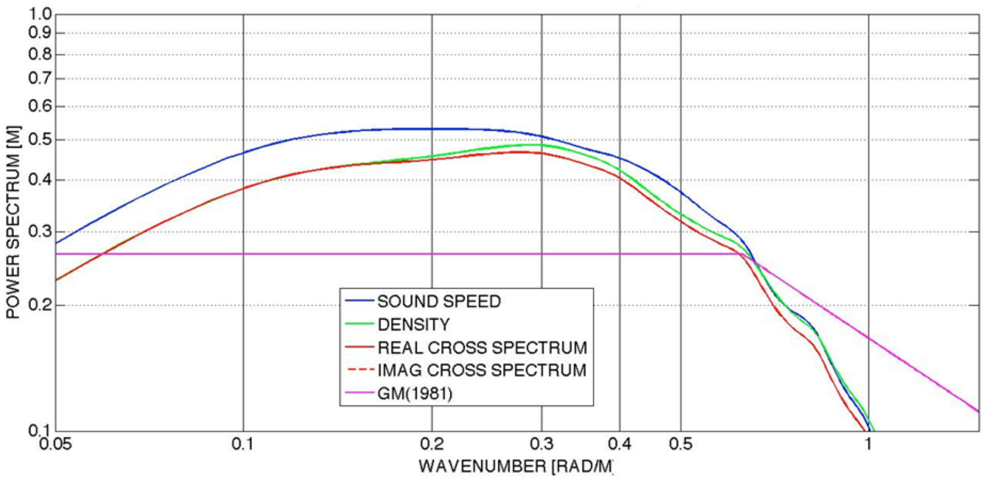

Figure 4 The average spectra from the 2009 experiment, for which all profiles were west of 127° E. The results are very similar to those in 2010, restricted to be west of 127° E.

Towed CTD chain

The calculations described above give vertical wavenumber spectra, but say nothing about the horizontal structure of the fluctuations. Enough is known about internal waves, that we have some confidence in making a model for the horizontal, but we have much less confidence in the horizontal structure of spice. In the absence of such information, it is generally assumed that the geometry of spice is the same as for internal waves, but there is no good reason for that assumption to hold. To measure the horizontal and vertical together, for both internal waves and spice, a towed CTD chain has been used. A number of CTD units are mounted along a cable, and that cable is towed by a ship. Such a chain was used in a shallow-water experiment in 2006, and later in the 2010 Philippine Sea experiment.

Unfortunately, a conclusion of the use of the CTD chain is that the particular hardware is inadequate for quantitative use. More recently, Ren-Chieh Lien and collaborators replaced the CTD units from a German manufacturer with reliable units made by Seabird Electronics, with much greater success. If Dr. Lien participates in future acoustics experiments with his towed chain, we can expect to be able to reliably model internal waves, spice, and ocean fronts for use in acoustic propagation calculations.

Coupled Mode Calculations

Coupled modes are the basis for a full-wave propagation calculation through sound speed variability, yet they provide more insight than parabolic equation calculations. A new highly accurate coupled mode code has begun to be applied to long-range, low-frequency propagation. A very peculiar feature relating adjacent modes is found when a single moderately high mode is sent. This feature would rule out the validity of transport theory under the textbook validity of the transport approximation, but this condition is far too pessimistic; the validity of transport theory remains an unanswered question.

Initial conditions were chosen to be mode 50 at 100 Hz. Propagation for 1200 km was calculated. Loss processes were assumed absent, so conservation of intensity could be used to test the accuracy of the numerical propagation scheme. The sum over modes of the modal intensities, which is the same as the vertically integrated horizontal intensity, was found to be constant to 1.3 parts per billion over the 1200 km range. Many other codes do not pass this test. [Technical note: This is the one-way equation intensity, which differs slightly from the Helmholtz intensity.]

Results of propagation through one particular realization of a Garrett-Munk internal wave field are shown in figure 5. The deep arrivals correspond to the higher modes that get produced by internal waves. For example, suppose mode 70 is created from mode 50 at 600 km. This would arrive at 1200 km at the same time as an unscattered mode 60, and would extend deeper because mode 70 has a deeper lower turning depth than mode 60.

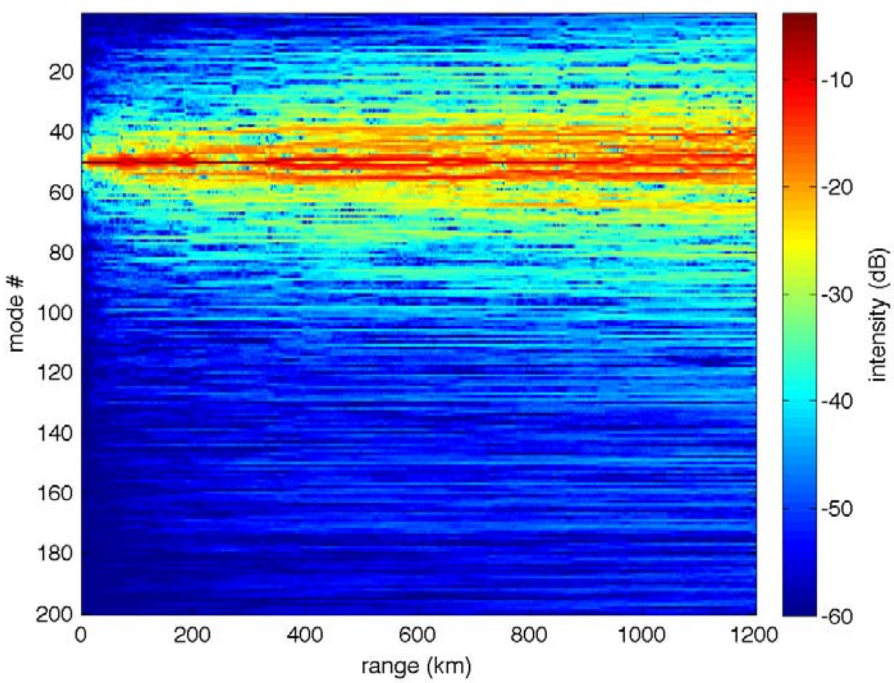

Figure 5. Mode intensities for the 200 retained modes at 100 Hz. The initial condition is pure mode 50.

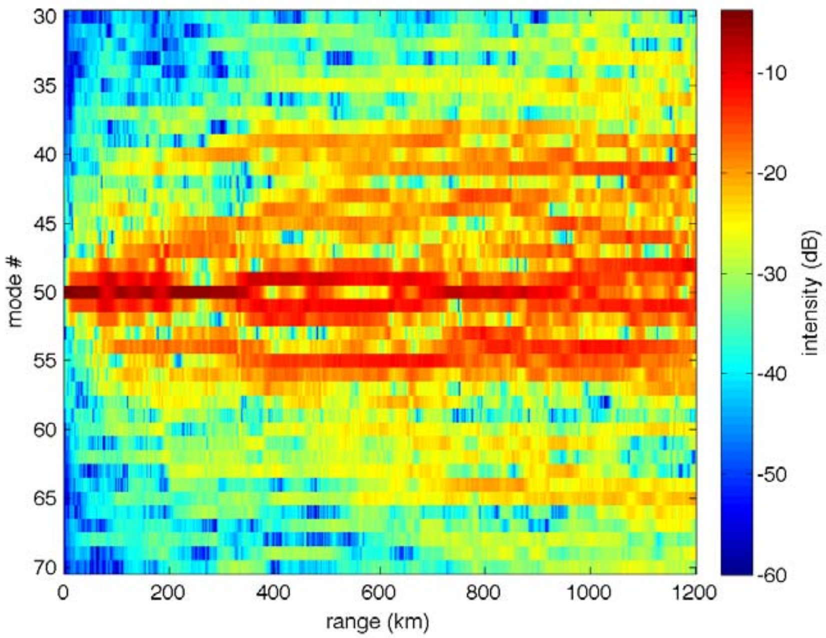

Figure 6 A magnification of figure 5. One sees that mode 50 becomes very weak, most notably between 400 and 600 km, but later, around 750 km, again dominates the intensity.

A magnification of this figure is shown in figure 6. This shows a very strange phenomenon. Several times, the starting mode becomes very small in intensity, only to regain its dominance later. The most notable of these events in this particular realization of the internal wave field is a 200 km stretch between 400 and 600 km. At two ranges in this interval, mode 50 is 30 dB down, only to later return to nearly half the intensity it started with. Figure 7 shows mode 50 compared to the sum of the four neighboring modes, and to the sum of all five of these modes. One sees that when mode 50 decreases suddenly, the four neighboring modes increase by about the same amount, and vice-versa. The sum of all five modes behaves qualitatively as one would expect each mode to behave.

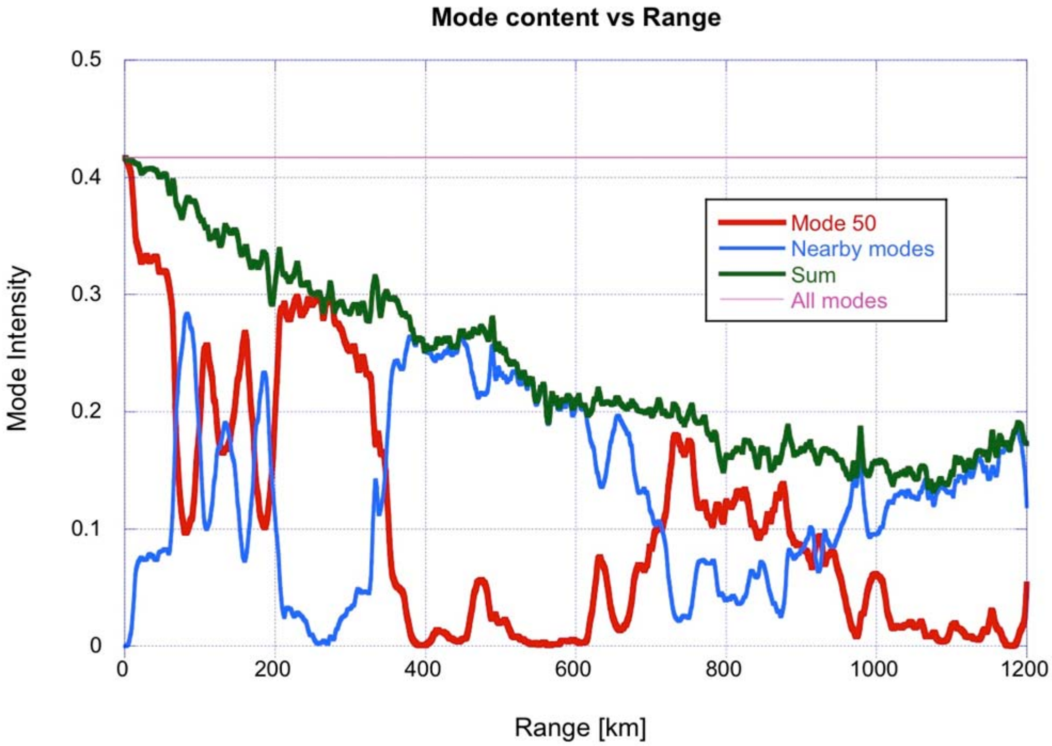

Figure 7 The strange behavior of mode 50 (the starting mode) is mirrored by the four neighboring modes (nearly equally split between the smaller two modes and the larger two, not shown). The sum of all five qualitatively resembles the expectation from the concepts that go into transport theory, whereas the individual modes strongly disagree with that expectation.

Because the behavior of the starting mode is so strange, it was verified that solving the PE with the same initial condition, and projecting onto modes showed the same phenomenon. This phenomenon is not understood, but it may be connected with the scattering being almost completely near the upper turning point of the mode, and with the existence of sharp arrivals in the time-depth plot, know for its shape as the accordion.

Transport Theory

The sharp transitions of mode 50 shown in figure 7 are inconsistent with the textbook condition of validity for transport theory, which requires transitions to be much smaller than an e-folding. However, work I did a few years ago shows that the textbook condition applies to a form of transport theory not used in practice, and is far too pessimistic for the commonly used form. However, these results suggest that a verification of transport theory is in order. (John Colosi verified the application to lower modes.)

Preliminary comparison of the simulations with Dr. Colosi's transport theory support the correctness of the transport theory results.

This work is continuing, currently under a grant with Dr. Jim Mercer as PI.